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FLUORSPAR PROCESSING PLANT AIRBORNE DUST STUDY DUST DISPERSION AND VENTILATION ANALYSIS USING TRACER GASES

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ABSTRACT

A dust survey was conducted in a fluorspar (CaF_2) milling and processing plant to assess the exposure of personnel to concentrations of total insoluble fluoride compounds (F^-) and respirable quartz dust. In the course of the study, Time-Weighted Average (TWA) concentrations of quartz were measured with sampling pumps operating at 1.7 L/min and 10 mm nylon cyclones. Total airborne fluoride concentrations were also obtained at a flow rate of 1.7 L/min directly on PVC filter discs. Sampling stations in the process building were chosen primarily as a function of personnel location during a normal shift. In addition to TWA sampling, continuous respirable dust monitoring was conducted at the crushing station close to the south end of the building and at the north end where flotation and separation equipment were located. As well as conventional ventilation measurements, tracer gas releases were performed to analyze the direction and rate of spread of contaminants from various points in the building. These releases also allowed the determination of average air residence times and contaminants clearance times out of the plant. Exhaust fans located on the roof were also rated using these same releases. Results of the tracer gas study were valuable in interpreting airborne dust data. Airborne respirable quartz concentrations were relatively high everywhere in the plant, demonstrating the influence of crushers as a major dust source. This observation was supported by the tracer gas release performed at the crushing station which indicated prevailing south to north air movements in the plant at the operating platform level.

Respirable dust concentration monitored as a function of time showed a rapid rate of decrease in dust concentration when crushing ceased. This was supported by tracer gas clearance times of about 20 min. Tracers, therefore, show promise in helping industrial hygienists obtain firm quantitative data as opposed to more qualitative results provided by anemometry and smoke tubes in this type of industrial setting.

Key words: Airborne dust; Tracer gases; Ventilation analysis.

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ÉTUDE DES POUSSIÈRES ATMOSPHÉRIQUES D'UNE USINE DE TRAITEMENT DE SPATH FLUOR ANALYSE DE VENTILATION ET DE DISPERSION DES POUSSIÈRES AU MOYEN DE GAZ TRACEURS

M.G. Grenier*, S.G. Hardcastle*, G. Kunchur+ et K.C. Butler**

RÉSUMÉ

Une étude sur les poussières a été menée dans une usine de concentration et de traitement de spath fluor (CaF_2) dans le but d'évaluer l'exposition du personnel aux concentrations des composés de fluorure insoluble total (F^-) et de la poussière de quartz respirable. Au cours de l'étude, les concentrations moyenne pondérées dans le temps (MPT) de quartz ont été mesurées à l'aide de pompes d'échantillonnage débitant 1,7 L/min dans des cyclones de nylon de 10 mm. Les concentrations de fluorure atmosphérique total ont aussi été obtenues à raison de 1,7 L/min, directement sur des disques filtrants en PVC. Les points d'échantillonnage dans le bâtiment ont été choisis principalement en fonction de l'emplacement du personnel pendant un poste de travail normal. En plus d'échantillonner les MPT, on a contrôlé les poussières respirables en continu au poste de concassage près de l'extrémité sud du bâtiment et à l'extrémité nord où le matériel de flottation et de séparation était situé. En plus des mesures de ventilation classiques, des gaz traceurs ont été libérés pour analyser la direction et la vitesse de dispersion des contaminants à partir de divers points dans le bâtiment. Ces gaz ont aussi permis de déterminer les temps de séjour moyens de l'air et les temps d'évacuation des contaminants à l'extérieur de l'usine. Les ventilateurs d'évacuation situés sur le toit ont aussi été évalués par la même occasion. Les résultats de l'étude aux gaz traceurs ont été utiles dans l'interprétation des données sur les poussières respirables. Les concentrations de quartz atmosphérique respirable étaient relativement élevées partout dans l'usine, démontrant que les concasseurs sont une source importante de poussière. L'observation a été confirmée par les gaz traceurs libérés au poste de concassage qui ont révélés la dominance des déplacements d'air sud-nord dans l'usine à la hauteur de la plate-forme de concassage.

Le contrôle de la concentration de poussières respirables en fonction du temps a révélé qu'elle diminuait rapidement lorsque le concassage cessait. Cela a été confirmé par les temps d'évacuation des gaz traceurs d'environ 20 min. Les traceurs semblent donc un moyen prometteur pour aider les hygiénistes industriels à obtenir des données quantitatives fiables contrairement aux résultats plus qualitatifs produits par l'anémométrie et les tubes à fumée dans ce genre d'environnement industriel.

Mots clés: Poussière atmosphérique; gaz traceurs; analyse de ventilation.

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INTRODUCTION

The use of tracers, radioactive and non-radioactive, is not new and dates back to the 1950's. At that time such techniques were put to use in underground mines to characterize respirable dust dispersion under a variety of conditions, including ore breaking and blasting operations.(1-2) The effort required and the logistics involved during such studies were considerable given the state-of-the-art in tracer technology. With the refining of gas chromatography and given some of the advantages of using tracer gases as ventilation networking tools, this field has grown considerably and new applications are continuously being developed.

The idea behind tracers is to release a known amount or concentration of a stable and safe substance that will readily mix with ventilation air. Sulphur hexafluoride is an ideal candidate which is not likely to be found in most industrial environments. Air/gas samples are then collected in strategic locations and analyzed using a gas chromatograph. Depending on the type of release and on the sampling strategy used, several variables may be obtained that will accurately characterize the ventilation network. For example, air flow velocities, volume of air paths, gas/dust transit times, pollutants removal times, and weaknesses in ventilation systems such as leakage or uncontrolled recirculation may be determined with the help of tracers.

Renewed and dynamic efforts are now being made to refine tracer gas sampling and analysis techniques. CANMET's Coal Research Laboratories and Mining Research Laboratories have been active in developing and testing real-time and field-rugged gas analyzers able to detect several tracers simultaneously.(3-4) Sometimes these tools can be used to verify or facilitate analysis performed using conventional anemometry. In several instances, however, these techniques will allow industrial hygienists to characterize mine and mill ventilation and to interpret contaminant data in a way that is not possible using conventional ventilation measurement practices.

The work presented here had two main goals. First, a comprehensive airborne dust survey of the premises needed to be performed in specific locations and on personnel. Second, a tracer gas survey was planned simultaneously to help characterize airborne dust spread and removal rates.

LIMITS OF EXPOSURE TO RESPIRABLE QUARTZ AND FLUORIDES

The mine operation surveyed during this study is under the jurisdiction of a regulatory body which uses ACGIH (American Conference of Governmental Industrial Hygienists) guidelines to control safety and health practices.(5)

Quartz is toxic to lung macrophages and causes fibrosis of tissues in the alveolar regions. This substance is sampled using a 10 mm nylon cyclone preseparator to yield a respirable dust mass. Laboratory analysis will later reveal the mass of respirable quartz present in the sample. ACGIH guidelines for quartz suggest a threshold limit value (TLV) of 0.10 mg/m^3 for exposure during a normal 8-hour shift. Fluoride is the other regulated substance sampled during this survey. Unlike quartz, which is thought to primarily affect the lower portion of the respiratory system, fluorides may affect several parts of the anatomy via different entry routes. For this reason total, as opposed to respirable, dust samples are collected for the determination of exposure to fluorides. Exposure to excessive concentrations of these compounds may lead to a variety of symptoms ranging from mottling of tooth enamel to local corrosion of mucous membranes and chronic bone disabilities.(6) Guidelines for exposure to fluorides suggest a TLV of 2.50 mg/m^3 in the course of an 8-hour shift.

Work shifts during the study took place over a 12-hour period. Although guidelines covering 8-hour shifts are widely accepted and implemented, the issue gets relatively more complex when applying these TLVs to extended or unusual work schedules. It is generally accepted, however, that reduced recovery times warrant some adjustments of the TLV when dealing

with toxic substances. An in depth discussion of extended work schedules and TLV modifications to suit these is beyond the scope of this work. Interested readers should consult other studies on the subject.(7-8) For the needs of the present work, use will be made of TLV modifications suggested by Brief and Scala.(8) Their work recommends a 50% reduction of TLVs for exposure during a 12-hour shift. This implies values of 0.50 and 1.25 mg/m^3, respectively, for quartz and fluoride compounds.

EQUIPMENT DESCRIPTION AND METHODOLOGY

Respirable quartz dust sampling trains consisted of self-regulated pumps operating at 1.7 L/min. Pumps were calibrated for flow rate both before and after sampling sessions to detect any pump failures or flow irregularities. These were drawing dust laden air through a 10 mm nylon cyclone with the respirable fraction of dust being captured on a 25 mm silver membrane filter disc (5 μm) for gravimetric and quartz analysis. Filters were analyzed for quartz using X-ray diffraction. This method yields results with an accuracy of 10 μg or 10%.(9)

Insoluble fluoride sampling was conducted in a similar manner to that described for quartz. Airborne dust in this case was deposited directly onto 37 mm PVC filters thereby yielding a total airborne dust measurement. Samples were then analyzed according to NIOSH method 7902. The limit of detection for this substance was 50 μg.

Respirable dust concentration was measured as a function of time with MIE Corporation (Bedford, MA, U.S.A.) Miniram personal dust monitors. Data from the Minirams was kept by electronic data loggers and calibrated using parallel TWA concentration data. A 10 mm nylon cyclone at the inlet to the Miniram sensing chamber separated the non-respirable fraction.

TRACER GAS METHODOLOGY

Critical to tracer gas analysis is the precise control of a stable gas release, integrity of sample collection devices, and accuracy of analysis. The gas release is controlled by a standard 2-stage regulator and a length of capillary tubing to act as a critical orifice. This method has proven to supply a stable gas flow with fluctuations in the order of 1%. Gas samples were taken either directly into 30 mL disposable polypropylene syringes with air tight caps or into 3 L bags via self-regulated sampling pumps operating at 25 cm^3/min. The bagged samples provided TWA results which may then be decanted into 30 mL syringes for ease of handling and analysis. Bags may then be flushed and reused. Analysis of the samples was performed using a laboratory based gas chromatograph with an electron capture detector calibrated for a 1 to 100 ppb range which has a precision rating of ± 1 ppb.

The simplest tracer gas technique used here consisted of a continuous release of gas to create a steady state concentration throughout the plant. This method can supply information on three attributes of the airflow. First, by knowing the release rate and the final concentration (for example, at the exhaust fans) the airflow can easily be calculated using the following relationship:

$$Q = \frac{V \times 10^9}{C} \qquad (1)$$

where, Q is the airflow (m^3/s), V is the tracer gas release rate (m^3/s), and C is the steady state concentration of gas (ppb).

Second, upon stopping the release, it is relatively easy to monitor the decay in concentration as the gas is removed. This can provide a measure of the average air residence time and total clearance times for the ventilation system. This would not only help model the clearance of gaseous pollutants, but would also give a very good approximation of the dynamics of airborne respirable dust.

Third, measuring the levels of steady state concentrations of gas in various locations in the mill provides a measure of dilution and mixing in the plant. This will also demonstrate which areas are affected by dust sources in specific locations. A release at a dust source will simulate the influence of that source to contaminate the plant.

MILL DESCRIPTION AND SURVEY FORMAT

The operation where this study was conducted processes ore from three local sources to provide a constant percentage of fluorspar to the process plant. The mine and the process plant employ approximately 125 workers of which 35 people are dedicated to the process plant where this work took place. The plant crushes 900 tonnes of ore daily and recovers 230 tonnes of fluorspar.

Figure 1 shows a plan and a side view of the process plant. Included in the plan are area sample sites, main process equipment and personnel quarters. Ore enters the building in the south-west corner of the plant through a pan feeder and is processed by a jaw crusher (90 cm wide, 8 cm gap). Crushed ore is then sent outside to a storage bin which uses screens to either store ore smaller than 1.6 cm in diameter or send larger stones to either of the cone crushers inside the plant. Conveyors send the discharge from cone crushers back to the outside bin, thereby closing the loop. Ore stored in the bin is then fed to the ball mills which grind the material until it is ready for the flotation cells. The product of flotation is sent outside the building for thickening and brought back inside for the final step which consists of drying on a drum filter. The fluorspar from the filter is then stored outside the building until it is ready to be shipped.

The crushing and milling portion of the process plant is located in the south third of the plant, while the north portion is dedicated to the separation and drying processes. These two sections are not separated by

walls or partitions. The mill is also divided into two vertical levels, the ground floor and the operation platform where most of the sampling was conducted. Two large doors as well as smaller entrances give access to the building. These were kept closed at all times in order to conserve plant heat.

Figure 1 also shows sampling sites numbered 1 through 6 which were chosen as a function of personnel posting. Station 1 was located between the transfer points where ore feeding the two cone crushers enters the building. Station 2 was located on the cone crusher platform. Station 3 sampled the vicinity of the jaw crusher discharge, while Station 4 was located on the jaw crusher platform close to the operator. Station 5 was sampling in the walkway between the two ball mills, and Station 6 was located in the north end between the flotation cells and the drum filter. All stations were equipped with two sampling trains dedicated to respirable quartz sampling. Stations 2, 4, 5 and 6 were also monitored for fluorides. Stations 2 and 6 were chosen for monitoring of the respirable dust concentration as a function of time.

Three aspects of the plant ventilation were evaluated using tracers and gas chromatography. As mentioned before, these were the roof fan exhaust flow rate, the average residence time of contaminants, and the general flow patterns within the building. Figure 2 shows the gas release points and the gas sampling grid. The release points, denoted by large asterisks were chosen to yield the most information on general ventilation trends and the sphere of influence of what were thought to be the major pollutant sources. Releases were conducted at the jaw crusher discharge (Station 3), and the cone crusher platform (Station 2), and the flotation/filter area (Station 6). One release was performed per day in order to ensure complete dispersal of sulphur hexafluoride prior to attempting another release. Spot syringe gas/air samples were taken at the 18 stations making up the sampling grid. Using this grid pattern it is possible to build a gas concentration profile inside the

plant.

Four shifts were sampled for dust as part of the study. Sampling sessions were conducted from the beginning of the night shift (20:00 h) until crushing stopped indefinitely when the outside bin was filled. Typical sampling sessions lasted from 5 to 7 hours. TWA dust concentrations were calculated over the full 12 hour shift, assuming crushing was not performed during the remainder of the shift. If crushing did indeed resume during the rest of the shift, the TWA concentrations would be underestimated. Three out of the four shift logs kept by plant staff indicated that no further crushing took place during the remainder of the shift, while 30 min of crushing was performed on the fourth shift after the samplers were removed. Five people worked the evening shift, and 4 respirable quartz sampling trains were issued. Surveyed personnel included the senior, the filter, the flotation and the crusher operators.

Existing dust control methods in the process plant consisted of enclosures and water spray bars at conveyor belt transfer points. Roof fans were used to exhaust air from the building at a total flow rate of 21 m^3/s (45 kcfm). These fans are located as shown in Figure 2. No enclosures or mechanical exhaust systems were installed in order to capture or remove dust produced by crushers at the time of the survey.

RESULTS OF DUST SAMPLING AND MONITORING

Table I lists a summary of TWA samples collected at the 6 sampling stations and on personnel. Shown in the table are the number of samples obtained at each location as well as the total and respirable dust concentrations measured over 12 hour shifts. The column on the right (column 6) lists the airborne respirable quartz fraction calculated from the ratio of values in columns 5 and 4, respectively. The index of variability associated with values in Table I is the standard variation of results.

Table I shows that samples obtained at Stations 2 to 5 have comparatively higher levels of airborne respirable dust and quartz. In the case of Stations 2, 3 and 4, this was expected since the rock breaking operations were suspected of being major producers of airborne respirable dust in the building. High concentrations of respirable dust in the mill area (Station 5, north of the crushers) were not easily explained since the mill process is very wet and is not expected to produce much airborne dust. The high concentrations measured at Station 5, therefore, are probably produced by the crushing operation and dust is then slowly transported by northbound air currents as will be shown later by tracer gas results.

Sixty-two samples were collected over a span of 4 working shifts. Of these, 46 were obtained from Stations 1 to 6, and 16 were personnel samples. Quartz analysis of the 62 samples revealed that 25 (40%) of the samples were in excess of the TLV for an 8 h shift. Transposing these results to a 12 hour shift, and using the Brief and Scala method for TLV reduction it was found that 45 (72%) of the samples were in excess of the reduced TLV. Personnel samples showed that 8 of 16 (50%) of the samples were over the reduced TLV of 0.05 mg/m^3. None of the samples showed concentrations in excess of the 0.10 mg/m^3 TLV for an 8 hour shift. Job classification did not seem to significantly affect exposure of monitored personnel to respirable quartz as can be seen from the low value of the standard deviation for respirable quartz on personnel (0.05 ± 0.02 mg/m^3).

From column 6 it first appears that the percentage of respirable quartz dust measured from total respirable dust samples is fairly constant at all stations. Actual values from the 62 samples collected range between 18 and 38% with an average of 27.5%. This range is credible in light of the fact that mill ore composition tests have shown an ore silica content of 39%. Figure 3 shows these quartz fraction averages for each station and personnel. The figure shows quartz fractions higher than the average from samples

collected at the cone crusher platform, the jaw crusher discharge onto the belt, and at the ball mill sampling station. Other stations and personnel samples have quartz fractions lower than the 27.5% average.

Table II shows the results of insoluble fluoride TWA concentration measurements. First, these concentrations were in every case well below the reduced TLV for fluorides. As such, therefore, no further mention need be made of the fluoride results from a health standpoint. Worthy of note, however, is the fact that the variability (mean deviation) is very low indicating reproducible results on a day to day basis. Also, fluoride results are very similar to quartz data in that wherever quartz levels are high in the plant, fluoride levels are higher also. Similarly, low quartz and fluoride concentrations are found in the same plant locations. This was not completely expected as it was anticipated that significant amounts of fluorides would be measured at Station 6 as sampling there was conducted close to the finished mill product (CaF_2). The results would indicate that flotation and drying are relatively small contributors of both quartz and fluoride in the plant.

Figures 4 and 5 contain the results of respirable dust sampling as a function of time. Figure 4 was obtained from data collected at Station 2 (cone crusher platform), and Figure 5 from data simultaneously collected at Station 6 (flotation/filter area). Over the span of time where sampling was conducted, it can be observed that the average respirable dust concentration is higher at the cone crusher platform than it is in the flotation area. This is reflected in TWA results shown earlier. Furthermore, the variability of data as measured by the standard deviation of the average is greater at the cone crusher due to the proximity of a major dust source. Both graphs indicate that crushing started shortly after 20:00 h, and dust concentrations increase from a baseline of about 0.10 mg/m^3. Both graphs are fairly well synchronized showing the effect of crushing throughout the plant. Closer examination of these figures reveals a time lag between both curves suggesting

that changes in production taking place in the crusher area are felt at the other end of the building within a few minutes.

TRACER GAS AND VENTILATION DATA ANALYSIS

As was mentioned earlier, 3 individual tracer gas releases were performed, one during each of the last 3 sampling shifts. Fan performance evaluation, average residence and total clearance times, and general mill ventilation patterns were established during each of the releases.

Two assumptions were made in the measurement of the average airflow rate of fans. First, it was assumed that all three fans were exhausting at a fairly high rate of flow and that the fan outlets were the only possible gas exit points in the mill building. Second, it was further assumed that the three fans were identical and should produce similar airflow volumes. The second assumption was verified with the help of vane anemometry. This method did not enable the measurement of a definite exhaust rate because of the difficulties involved in defining the cross-sectional area at the fan exhaust, but it was possible to estimate that all fans were operating at similar rates with 4% or less variability. Table III shows the results of vane anemometry performed on each fan on a daily basis using an identical traverse procedure. It can be seen that within the limits established by the standard variation of the overall average, it is not possible to differentiate one fan from another.

From SF_6 sampling of exhaust air from each fan, and using equation 1 and the above assumptions, it was determined that the average fan duty was 7.28, 7.01 and 6.80 m^3/s during releases 1, 2 and 3, respectively. The average fan volume, therefore, is 7.03 $\pm$0.17 m^3/s (14.9 $\pm$0.35 kcfm). These values compare favourably with the design duty of 7.08 $m/^3s$ (15.0 kcfm).

Once the airflow through the building is established, it is easy to determine the ideal concentration of gas in the mill if it was diluted and mixed evenly throughout. Observed deviations from this ideal mixture

situation will serve to establish the general air circulation trends in the plant. The air flow patterns are evident in the relative sulphur hexafluoride concentration profiles shown in Figures 6 and 7. These are obtained from grab samples collected in a grid pattern (shown in Figure 2) which are then processed by computer software to yield a profile in one of the two forms shown in the figures. The top diagram in these figures shows the relative equilibrium concentration of gas in a 2-dimensional contour line format. The bottom diagram gives a 3-dimensional appreciation of the same results. In both figures, the 100 relative concentration point refers to the equilibrium concentration of gas that would prevail if all the gas was diluted and mixed evenly throughout the mill.

Figure 6 shows that gas released in the south end of the building contaminates the whole mill. It is fair to assume that dust produced by the crushing operations will behave in a generally similar manner. The south to north air flow pattern is undoubtedly produced by a negative pressure created by the roof fans which in turn draw outside air into the building via the conveyor belt entry points in or close to the south end wall.

This is supported by data from Figure 7 which shows that gas released at the north end of the mill tends to remain in that area. These data support continuous dust monitoring traces and gravimetric sample results that demonstrated a definite link between activity in the crushing area and airborne dust concentration everywhere else in the mill. In fact it is possible to plot the equilibrium SF_6 gas concentration measured at Stations 1, 4, 5 and 6 during the cone crusher platform release versus the average TWA respirable dust concentration measured at these stations throughout the survey. In doing so we obtain the linear relationship shown in Figure 8. This shows a very good linear fit with a high correlation coefficient. Attempts to duplicate this for the flotation/filter release resulted in a totally uncorrelated set of data points. This shows that respirable dust

produced by the crushing operation in the south end of the plant is transported and behaves much like the tracer gas released at a single point on the cone crusher platform. This emphasizes the importance of the crushing operation as far as the plant contamination problem is concerned.

The final variables to be established during the gas releases were the process plant residence and clearance times. These are measures of the effectiveness of the ventilation system at removing and diluting pollutants. For the continuous injection method employed here, both these times can be measured as the gas concentration decreases once the injection is terminated. Here, the average residence time is defined as the time it takes for the gas to decay from its steady state concentration to 50% of that value. The clearance time is defined, in this instance, as the time required for the gas concentration to be reduced to less than 1% of its steady state concentration.

Figure 9 shows gas decay curves at 4 mill locations. These were obtained during gas releases 1 and 2. These graphs show a clear and rapid decrease of gas concentration when the source is removed (time zero). Visual inspection reveals residence times of less than 10 min and 90% clearance times of less than 25 min.

Fitting a logarithmic expression to these data resulted in the values shown in Table IV. This table shows residence times of less than 8 min. The short residence times are in agreement with the rapid dust concentration decrease observed in Figures 4 and 5 when crushing was halted.

CONCLUSIONS

As a result of this survey several recommendations were made including the installation of properly designed enclosures and mechanical exhaust systems on all three crushers, and regular maintenance of the existing water spray system used at conveyor belt transfer points. Until these changes are implemented, personnel working in the plant were encouraged to use appropriate

respirator masks since quartz dust levels in the building were, in most cases, in excess of the TLV.

Of more importance to the work presented here, however, is the role that tracer gases played and the credibility given to data interpretation. These techniques were instrumental, for example, in pin-pointing crushing as the most important dust source in the plant. Fan flow rate determinations were performed accurately in a matter of a few minutes.

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TABLE I - Summary of Total and Quartz Respirable Dust Data

Station	Description	Samples	Resp. Dust Conc. (mg/m^3) Total	Quartz	Quartz
1	Cone Feeder	8	0.20±0.08	0.04±0.02	22±3
2	Cone platform	8	0.57±0.31	0.20±0.13	32±2
3	Jaw discharge	7	0.54±0.10	0.17±0.04	31±2
4	Jaw platform	7	0.35±0.06	0.09±0.02	26±1
5	Ball mill	8	0.47±0.09	0.15±0.04	31±3
6	Flotation	8	0.18±0.03	0.05±0.01	27±5
-	Personnel	16	0.20±0.06	0.05±0.02	25±3

TABLE II - Summary of Insoluble Fluoride Dust Data

Station	Description	Samples	TWA Conc. (mg/m^3)
2	Cone platform	4	0.19 ± 0.04
4	Jaw platform	4	0.17 ± 0.03
5	Ball mill	4	0.14 ± 0.04
6	Flotation	8	0.08 ± 0.01

TABLE III - Anemometer Traverse Determination of Roof Fan Air Velocity

Shift	Air Velocity (m/s) North Fan	East Fan	West Fan
2	-	-	10.47
	-	9.80	9.91
	-	9.95	10.48
3	9.87	10.25	9.59
	9.98	10.00	9.89
	10.03	9.76	9.45
4	10.61	10.56	10.02
	10.49	11.02	10.47
	10.40	10.02	10.36
Average	10.23	10.17	10.07

Overall ave: 10.15 $\pm$0.37 m/s

TABLE IV - Process Plant Residence and 99% Clearance Times

Location	Residence (min)	99% Clearance (min)
Jaw Crusher	6.6	43.8
Ball Mill	7.9	52.6
Flotation	6.7	44.8
Cone Crusher	5.0	33.6

FIGURE CAPTIONS

Figure 1 -- Plan and side elevation of the process plant surveyed showing major processes and dust sampling stations.

Figure 2 -- Tracer gas release points and sampling grid used to characterize process plant ventilation.

Figure 3 -- Respirable quartz fraction averages as a function of sampling station and personnel sampling.

Figure 4 -- Respirable dust sampling as a function of time at the cone crusher platform (Station 2).

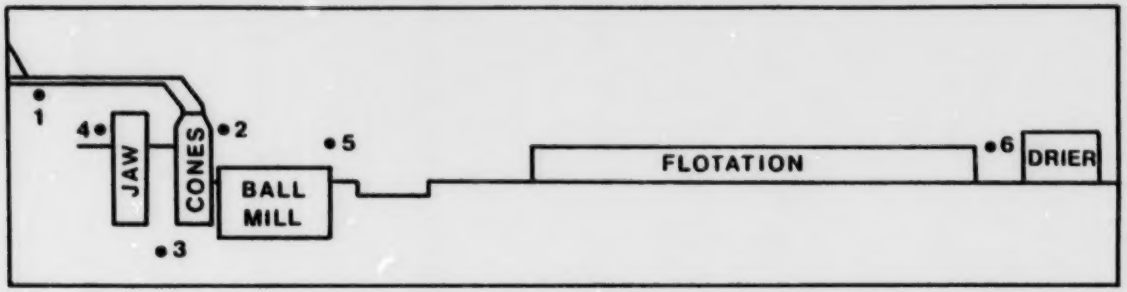
Figure 5 -- Respirable dust sampling as a function of time in the flotation/filter area (Station 6).

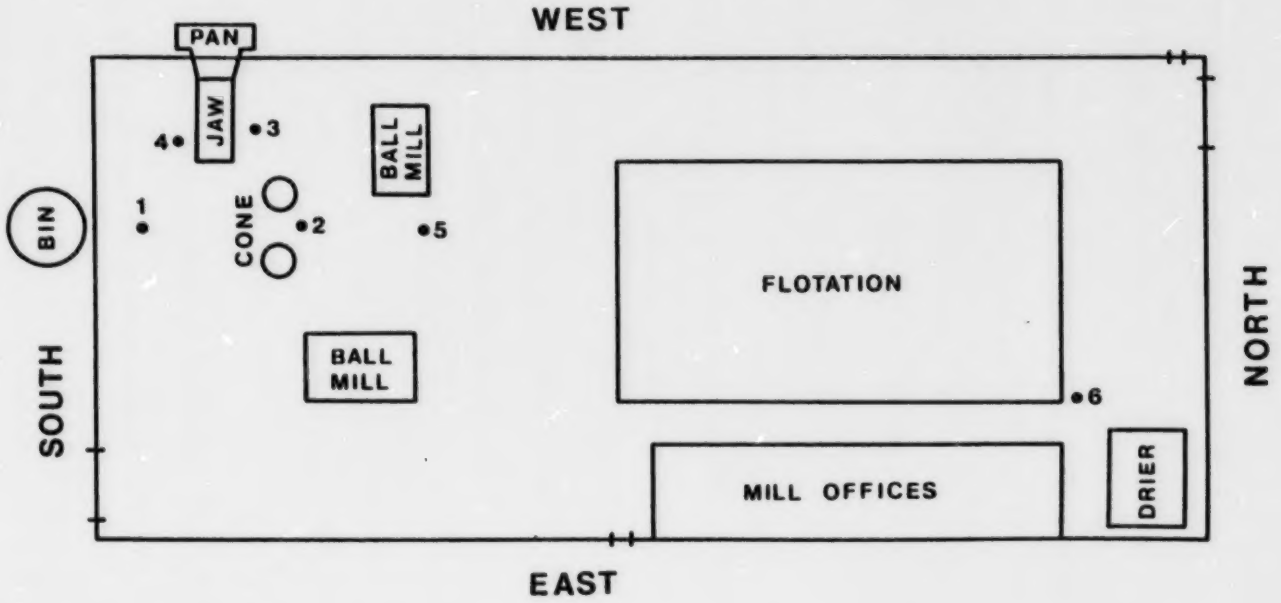
Figure 6 -- Equilibrium tracer gas concentration in the process plant from the cone crusher release point (Station 2).

Figure 7 -- Equilibrium tracer gas concentration in the process plant from the flotation/filter area release point (Station 6).

Figure 8 -- Correlation of TWA respirable concentration data and equilibrium tracer gas concentrations from the cone crusher platform release.

Figure 9 -- Tracer gas concentration decay curves upon termination of the gas release.





•- Location of sampling stations

Figure 1

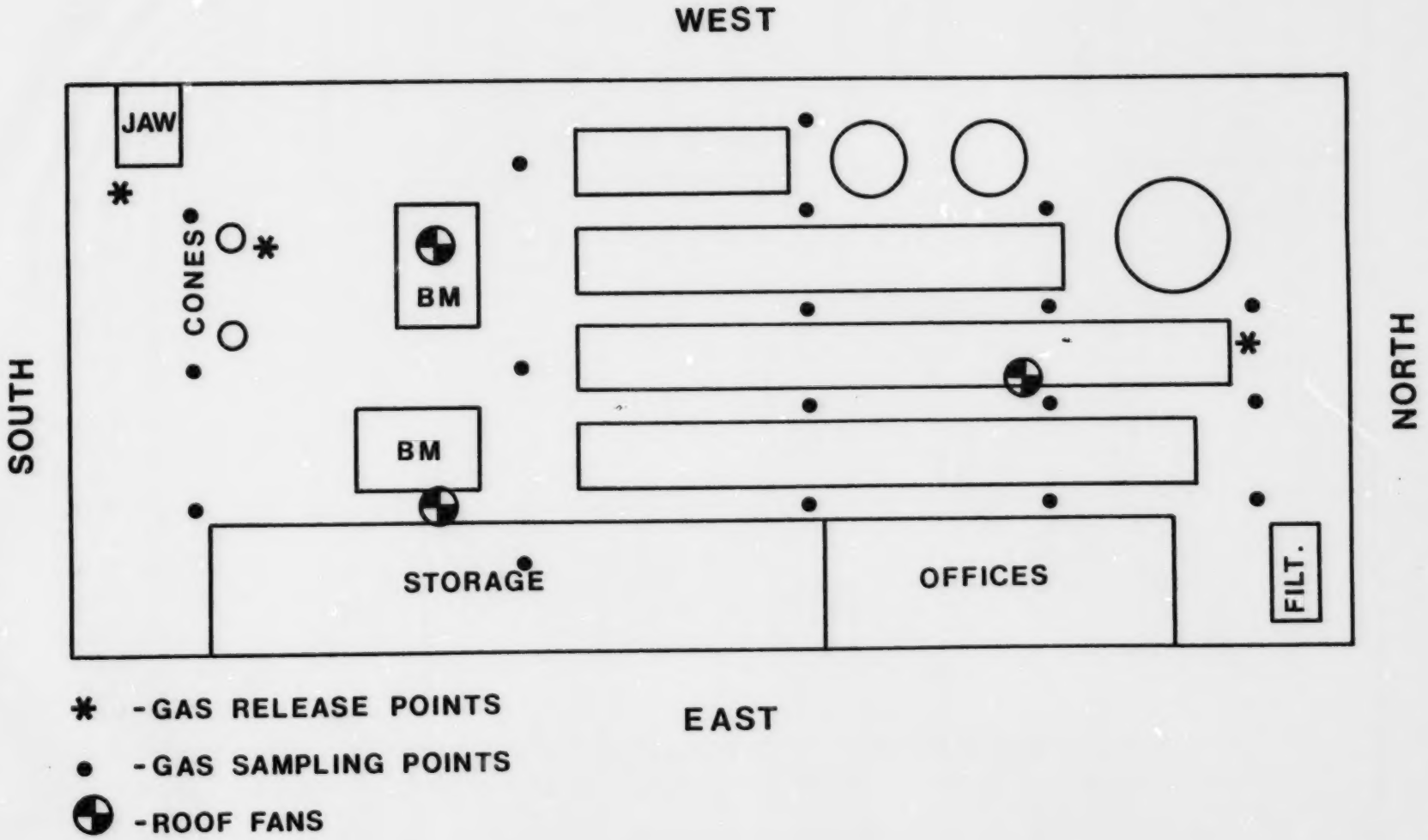

WEST
JAW
CONES
BM
BM
SOUTH
NORTH
STORAGE
OFFICES
FILT.
EAST
-GAS RELEASE POINTS
-GAS SAMPLING POINTS
-ROOF FANS

Figure 2

RESPIRABLE QUARTZ FRACTION
% RESPIRABLE QUARTZ
34
32
30
28
26
24
22
20
18
CONE CRUSHER PLATFORM
BALL MILL AREA
JAW CRUSHER DISCHARGE
FLOTATION DRIER AREA
JAW CRUSHER OPERATOR AREA
PERSONNEL SAMPLES
CONE CRUSHER FEED AREA
SAMPLE LOCATION / PERSONNEL

Figure 3

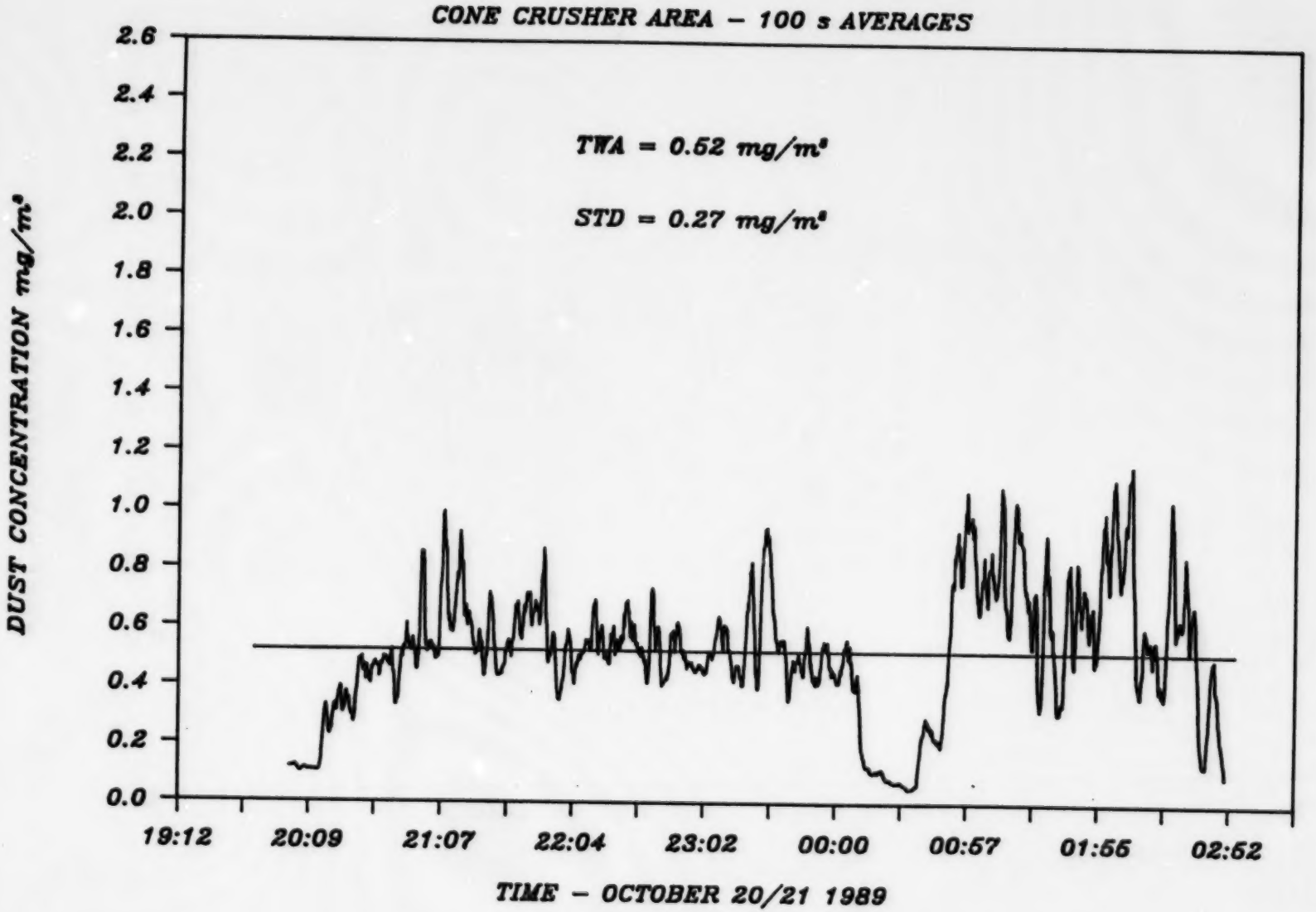

CONE CRUSHER AREA – 100 s AVERAGES
TWA = 0.52 mg/m³
STD = 0.27 mg/m³
DUST CONCENTRATION mg/m³
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
19:12
20:09
21:07
22:04
23:02
00:00
00:57
01:55
02:52
TIME – OCTOBER 20/21 1989

Figure 4

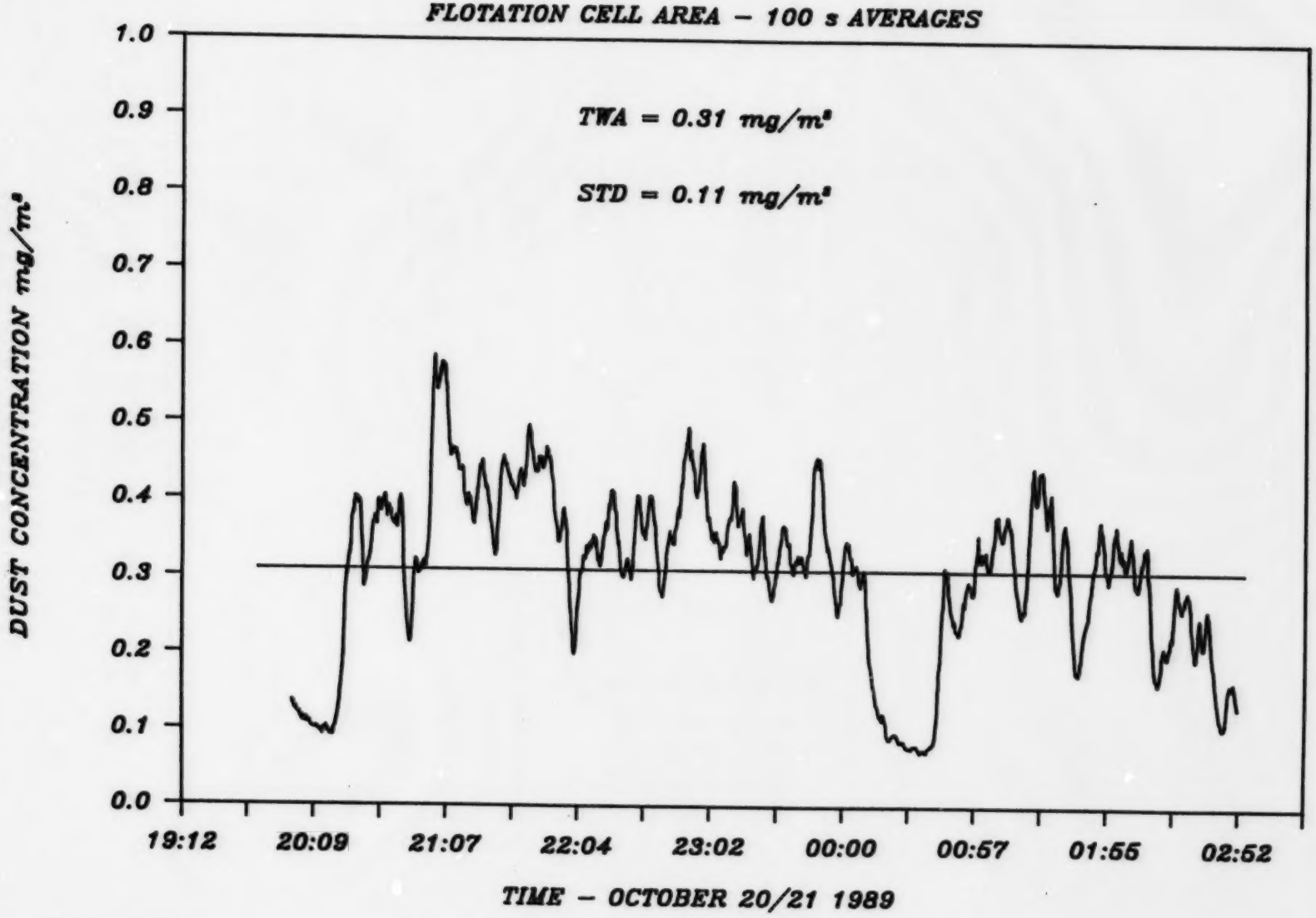
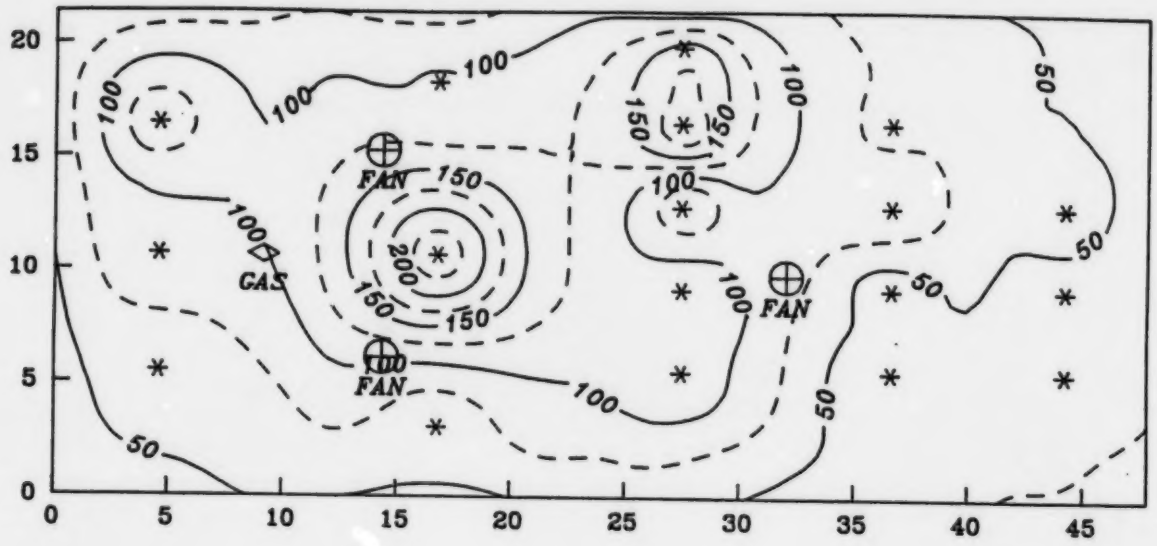

FLOTATION CELL AREA – 100 s AVERAGES
TWA = 0.31 mg/m³
STD = 0.11 mg/m³
DUST CONCENTRATION mg/m³
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
19:12
20:09
21:07
22:04
23:02
00:00
00:57
01:55
02:52
TIME – OCTOBER 20/21 1989

Figure 5



SF6 TRACER GAS DISTRIBUTION – CONE RELEASE

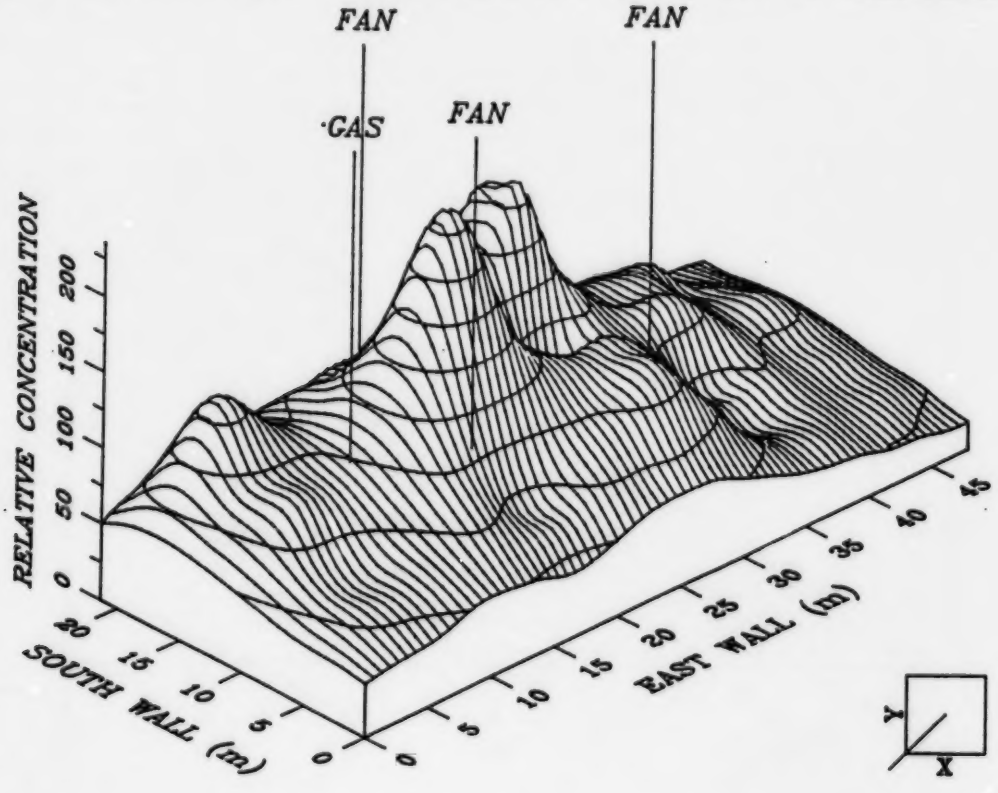
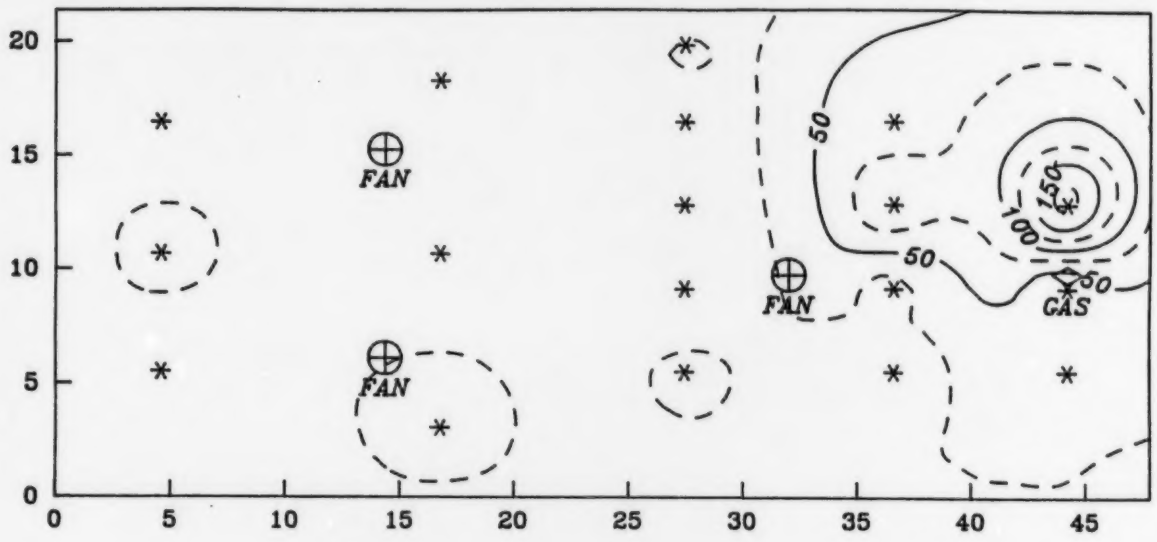


Figure 6



SF6 TRACER GAS DISTRIBUTION – DRIER RELEASE

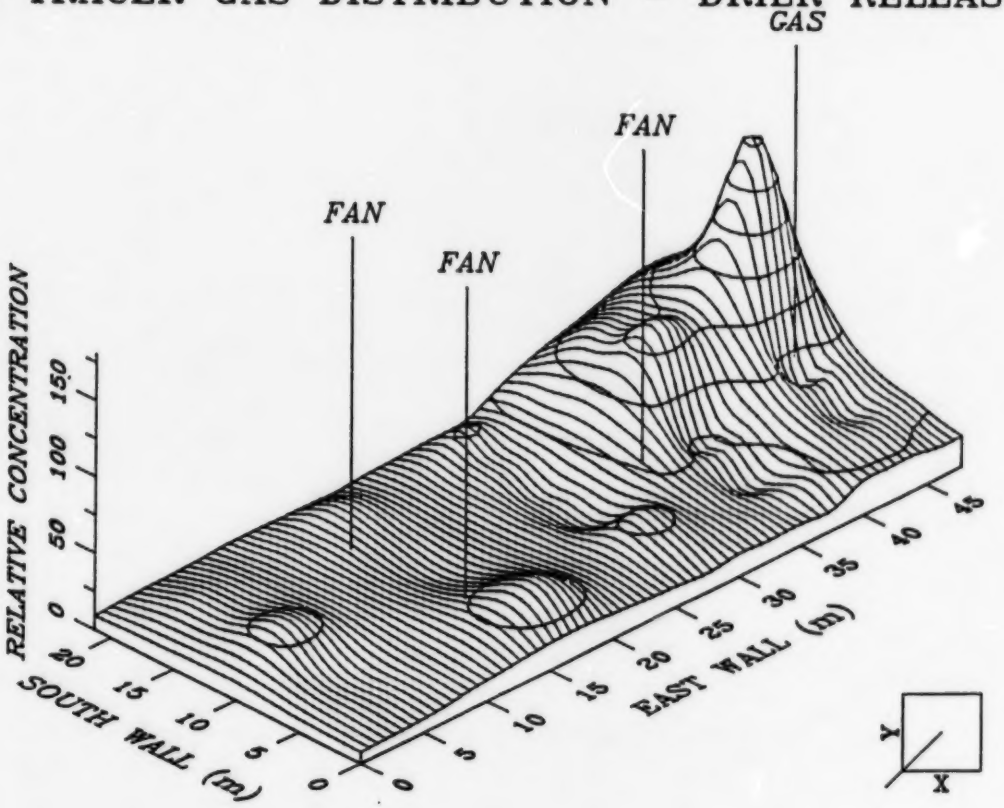


Figure 7

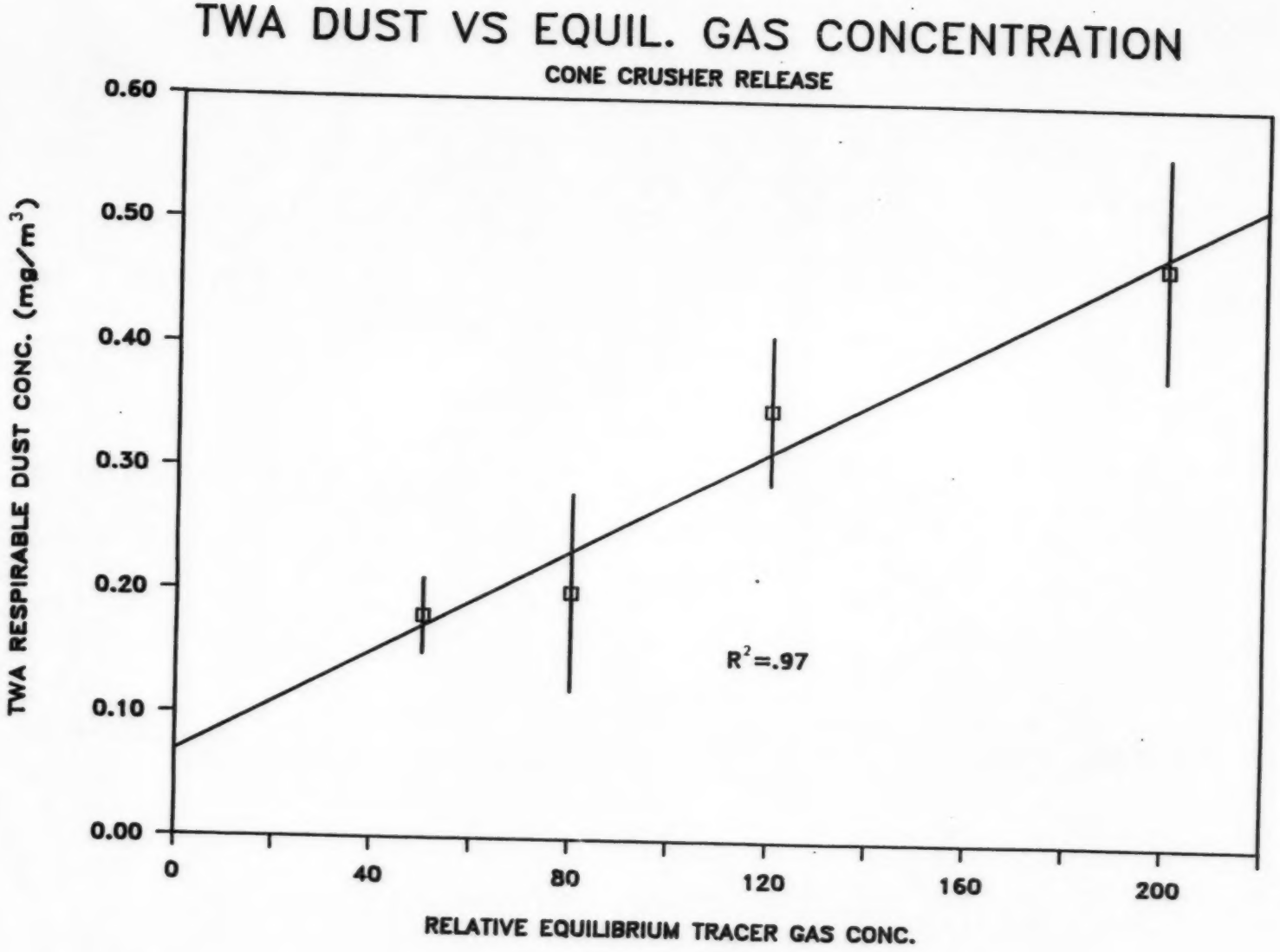
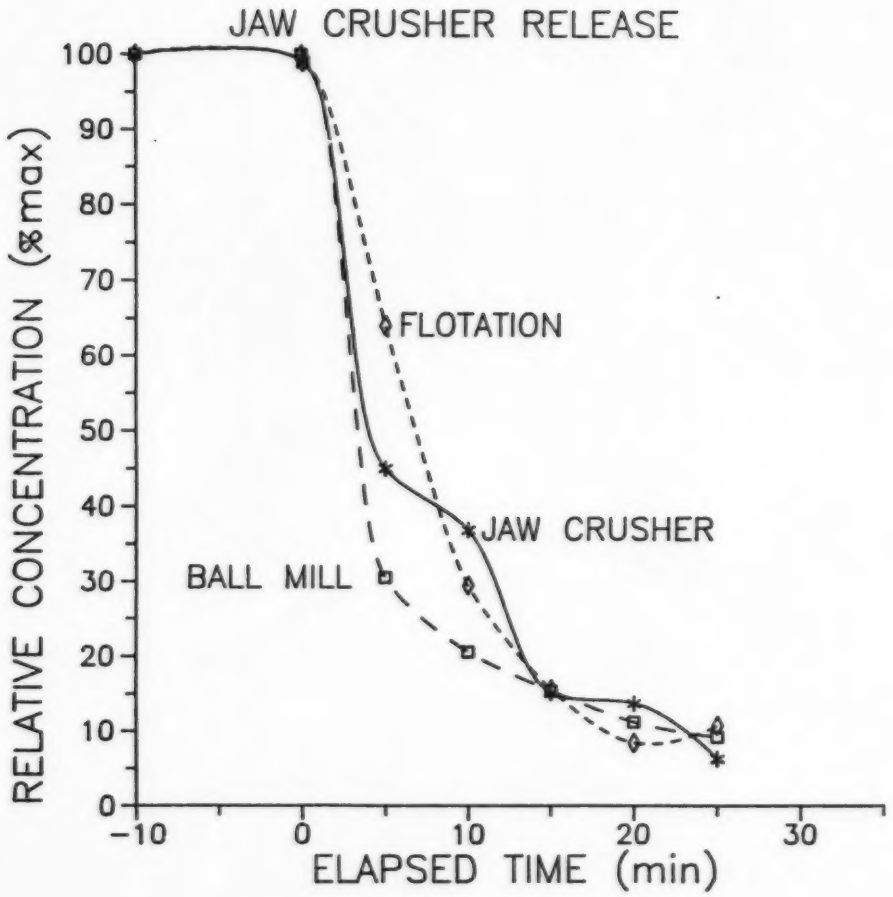

TWA DUST VS EQUIL. GAS CONCENTRATION
CONE CRUSHER RELEASE
TWA RESPIRABLE DUST CONC. (mg/m³)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
R²=.97
0
40
80
120
160
200
RELATIVE EQUILIBRIUM TRACER GAS CONC.

Figure 8

SF6 TRACER GAS INJECTION DECAY



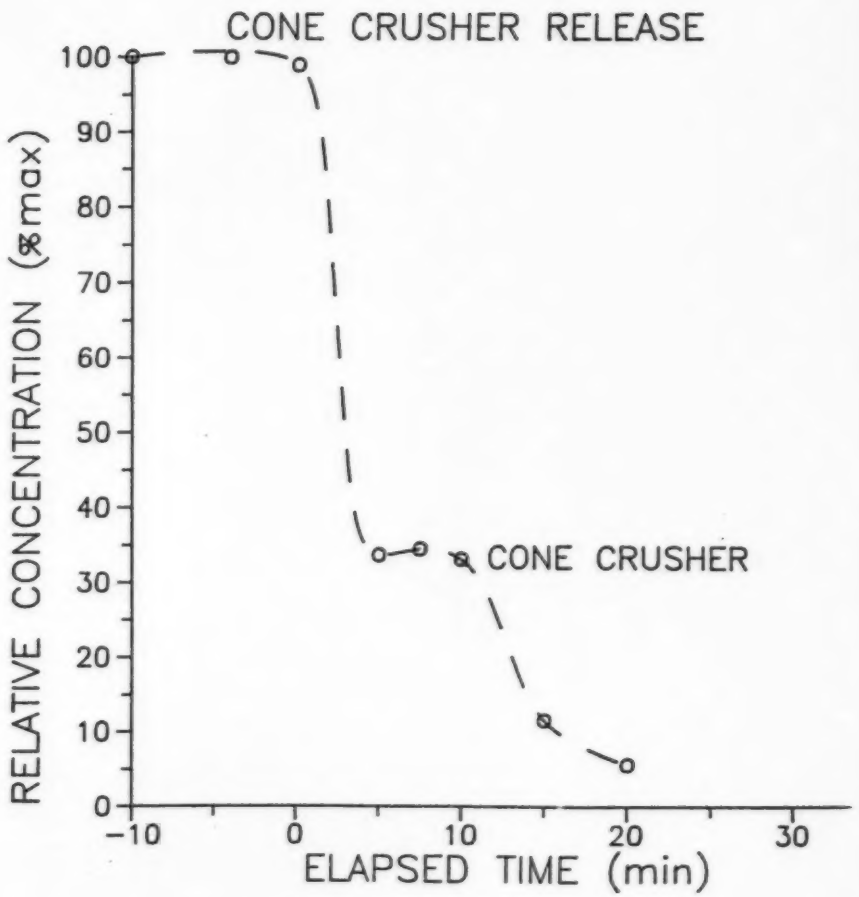


Figure 9